Contrib. Plasma Phys. **41** (2001) 2-3, 239−242

Experiments Using Laser–driven Shockwaves for EOS and Transport Measurements

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Received 22 September 2000, in final form 9 December 2000

Abstract

Laser–driven shocks have broken new ground in providing data on strongly coupled systems. One example is the measurements of the Hugoniot of hydrogen isotopes to over 300 GPa and the clear signature of metallic behavior at pressures of 60 GPa. The resulting fluid is strongly coupled ($\Gamma > 10$) and probably composed of ions, atoms, and molecules – a very difficult system to understand. The latest interpretation of these measurements is discussed. In addition, recent shock measurements on the hydrogen–bonded compound water – both EOS and reflectivity – are shown. The metallic signature for water is very different than that of hydrogen.

1 Introduction

A series of laser shock experiments on liquid deuterium has revealed a highly compressible equation of state (EOS) near 100 GPa where the ion–ion coupling parameter of the fluid Γ is > 10 [1], [2]. This regime of high density and extreme pressure is a strongly correlated, partially degenerate composite of molecules, atoms, and electrons making reliable experimental data essential as a guide to theory. Initial indications also showed that the fluid had been shocked into a metallic state [3]. These findings are important elements in the construction of models of large planets [4] and for predictions of fusion yield in inertial confinement fusion targets [5]. There has been considerable discussion of these results [6] and new experiments are underway to obtain EOS data on hydrogen isotopes in this regime [7], [8]. Although the laser–driven experiments on deuterium are still controversial, the laser EOS data at the metal-insulator transition (MIT) combined with gas–gun–shocked electrical conductivity measurements also at the MIT at lower temperatures [9], have provoked a reassessment of dense, finite-temperature hydrogen theory. New molecular dynamics results [10], [11] exhibit higher compressibility than tight-binding MD simulations reported earlier [12] ($\rho_{Shocked}/\rho_{Initial} = 4.6 vs. 4.1$) but do not achieve the compression of 6 seen in the EOS data, although they agree very well with each other. Recent quantum Monte Carlo (QMC) results [13] differ considerably with earlier QMC simulations [14] but also with the data. Unlike Ref. [14], the newer QMC results do not predict a first order phase transition at the MIT, a so–called plasma phase transition (PPT). Recent results by Saumon et al. [15] also modify their earlier predictions to show no PPT on the Hugoniot. Transport behavior – reflectivity and conductivity – can be used to investigate the nature of dense hydrogen isotopes near the MIT. Below we describe recent evaluations of D_2 shock reflectances that show no evidence of a PPT. For comparison, we also describe preliminary results on reflectivity measurements of a strongly shocked hydrogen-bonded compound: water.

2 Reflectance Experiments

Measurements of the reflectance of shocked liquid deuterium have been made. Each experimental target consisted of a metal pusher capping a liquid–D_2–filled cell that was irradiated either by direct laser illumination or soft x–rays produced in a laser hohlraum. The shock driven into the pusher then released into the D_2. The opposite end of the cell was sealed by a sapphire window through which a VISAR probe laser was focused, yielding a time– and 1D–space–dependent recording of the velocity of the reflecting surface and its reflectance [16]. After breakout, the reflecting surface is the shock front in the D_2 propagating toward the VISAR [3]. The shock reflectance was measured relative to that of the pusher surface prior to breakout. This latter value can be referenced to known values of the metal pusher reflectance, providing a calibrated reflectance for the D_2 shock. The result of such a measurem! en! t is Reflectance–*vs.*–Shock Speed at the probe laser wavelength. Two types of shock reflectance measurements were made: steady and attenuating shocks. In the first type the laser drive employed a constant intensity and was on as long as practicable in order to produce a constant–speed shock. This produced a single value of reflectance at a single shock speed. The constant–shock–speed data are shown in Fig. 1 as single points. Three different probe wavelengths were employed: 1064, 808, and 404 nm. The horizontal bars in the figure are Drude estimates for the three wavelengths. Reflectances from attenuating shocks are shown in Fig. 1 as the continuous curves for 1064 and 808 nm. The laser drive for these shots was impulsive so that the shock continually decelerated in the D_2. Since the VISAR diagnostic always viewed the shock front and the shock front is always on the Hugoniot, the effect is to sweep out a stream of measurements along the Hugoniot. The first thing to note is that the reflectance behavior is consistent at all three probe wavelengths, consistent with a Drude picture and are similar to those of liquid metals. [17] Secondly, the value of reflectance one would expect from a dielectric under 6–fold compression is about 5%. The reflectance values recorded in the experiments are many times that value, showing that a conducting state is being attained. Thirdly, the attenuating shock data form continuous curves. There is no indication of a PPT in these Hugoniot data, an important consideration for theories on strongly coupled matter. Finally, in Fig. 1 the shock speed measurements have been translated into pressure using a fit to the Hugoniot data [1], [3]. We conclude that the conducting state begins around 20 GPa on the Hugoniot and a metallic state has been attained by 60 GPa. This conclusion is supported by an analysis of the parameters of the Drude conductivity model given the reflectance data. The charge carrier density enters through the plasma frequency in the Drude model and can be estimated, where the carrier density must be near 10^{23} cm^{-3}. The reflectance data do not conform to a simple band–gap–closure model for the deuterium MIT. [18]

3 Conclusions

The reflectance data clearly indicate a transformation from a nonconducting to a conducting state starting at $\sim$ 20 GPa and saturating $\sim$ 60 GPa on the D_2 Hugoniot. This is in the same regime as the EOS data begin to exhibit high compressibility so we determine that at least part of the cause of the high compressibility is due to crossing the MIT. The EOS data show that compression continues to increase on the Hugoniot above 60 GPa, so we assume that formation, excitation, and dissociation

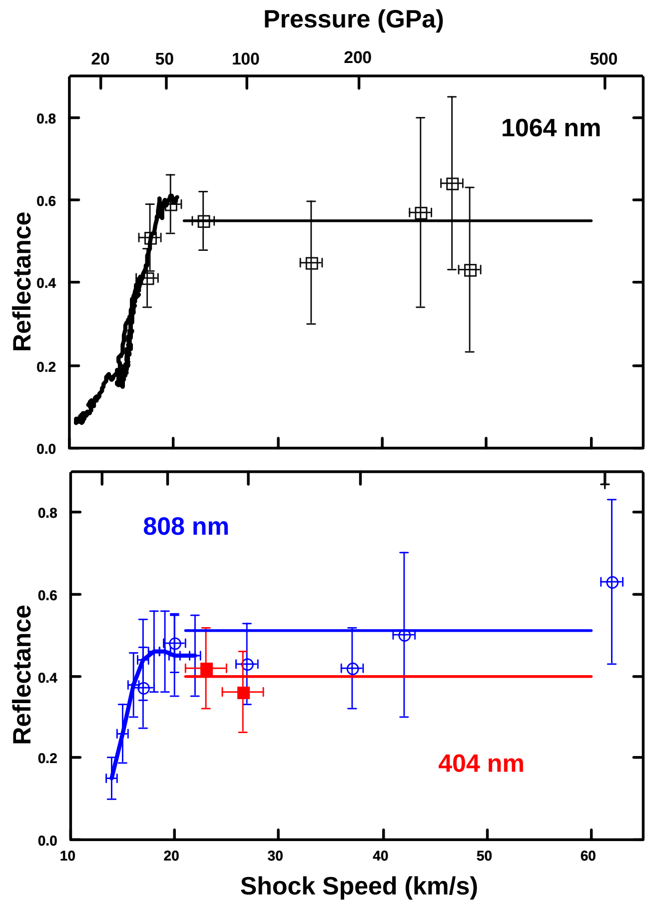

Fig. 1: Top: reflectance at 1064 nm of the shock front in liquid deuterium. Points are steady–shock, single measurements. The curve is from attenuating shocks that reveal reflectance over a range of shock speeds. The horizontal line is the value of an estimated Drude model reflectance. Bottom: same as top for 808 and 404 nm wavelengths. Open circles are 808 nm; squares are 404 nm. The continuous curve is 808–nm reflectance from an attenuating shock.

of molecules, along with the interaction of the various molecules, ions, and atoms, make further compression possible until $\sim$ 100 GPa. There is no direct evidence for molecular influence at these pressures; an experiment that probes molecular states of shocked hydrogen isotopes would be extremely valuable. We have recently performed reflectance experiments on a strongly shocked hydrogen–bonded compound — water. A preliminary measurement of the reflectance of water shocked to 500 GPa and allowed to decay to less than 140 GPa is shown in Fig. 2. The behavior is radically different from hydrogen isotopes. The reflectance slowly increases with pressure over 400 GPa, unlike hydrogen, where the reflectance goes from visible to saturation in 40 GPa. We expect to find many more degrees of freedom in water rather than hydrogen and the possibility of chemical reactions. We intend to pursue further experiments on strongly shocked water and other hydrogen–bonded compounds.

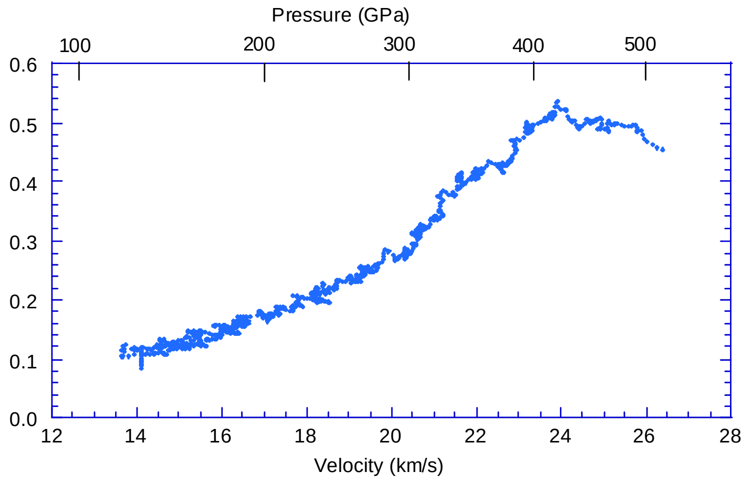

Fig. 2: Single–wavelength reflectance measurement of an attenuating shock in water from 500 to 140 GPa.

Acknowledgements

This work was performed under the auspices of the U.S. DOE by University of California Lawrence Livermore National Laboratory under contract No. W–7405–Eng–48.

References

[1] Da Silva, L.B. et al., Phys. Rev. Lett. **78** (1997) 483
[2] Cauble, R. et al., Phys. Plasmas. **4** (1997) 1857
[3] Collins, G.W., Science **281** (1998) 1178
[4] Guillot, T., Science **286** (1999) 72
[5] Dittrich, T.R. et al., Phys. Plasmas **6** (1999) 2164
[6] Young, D.A., Cauble, R., eds., High Pressure Research **16** (2000) special issue: Hydrogen at High Pressure
[7] Mostovych, A.N., et al., Phys. Rev. Lett. submitted (2000)
[8] Knudson, M.D. et al., Workshop on Warm Dense Matter, Vancouver (2000) unpublished
[9] Nellis, W.J. et al., Phys. Rev. B **52** (1995) 15835
[10] Collins, L.A. et al., High Pres. Res. **16** (2000) 313
[11] Hood, R.Q. et al., Workshop on Warm Dense Matter, Vancouver (2000) unpublished
[12] Lenosky, T.J. et al., Phys. Rev. B **56** (1997) 5164
[13] Militzer, B., Margo, W., Ceperley, D., Contrib. Plasma Phys. **39** (1999) 147
[14] Magro, W. et al., Phys. Rev. Lett. **76** (1996) 1240
[15] Saumon, D., Chabrier, G., Wagner, D.J., Xie, X., High Pres. Res. **16** (2000) 331
[16] Celliers, P.M., et al., Appl. Phys. Lett **73**, (1998) 1320
[17] Ashcroft, N.W. and Mermin, N.D., Solid State Physics (Holt, Reinhart, Winston, Orlando, 1976)
[18] Celliers, P.M., Phys. Rev. Lett. **84** (2000) 5564